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Luminous Surfaces for Architectural Lighting

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In the last several years architectural lighting has continuously advanced, replacing many of the unattractive and inartistic older types of lighting. One of the forms of architectural lighting, the luminous surface source, has led the advance in use. Unfortunately the technical information available on surface sources does not permit the design of such lighting from other than a decorative point of view. The use of artificial windows and laylights has been restricted because of the necessary provision for heat dissipation from these units, the considerable structural depth required for the mounting of these luminaires, the poor luminous efficiency of laylights, and the absence of a suitable brightness uniformity over the surface. This paper shows that it is possible to design artificial windows and skylights with a luminous efficiency approximating that of the direct lighting luminaires to which we are accustomed, and much higher than that usually obtained with built-in lighting; at the same time high uniformity of brightness is obtained over the surface.

THE study of the subject of this paper was suggested as a desirable supplement to the work presented in the paper, *Illumination Distribution from Surface Sources in Rooms*, printed in the February, 1936, issue of the TRANSACTIONS. In this paper data are presented showing how the luminous surface source may be utilized for good illumination, rather than merely as an architectural fancy. Lighting from large luminous expanses may combine the good qualities of indirect lighting with the high utilization efficiency of ordinary direct systems of lighting.

An analysis of the published technical data on surface sources shows that the most serious defects of the sources now in use are the

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low efficiency and economy of these devices; these defects result from a poor choice and design of the reflecting surfaces, an unwise choice of translucent, diffusing media, and an unnecessary subdivision of the light source with consequent excessive cost of energy and lamps. Moreover, in some cases the brightness distribution over the laylight has not been uniform enough for good appearance and eye comfort. In still other cases too little attention has been paid to limiting the depth of the unit, resulting in a considerable sacrifice of ceiling height to accommodate the luminaire.

The design of the surface source described herein was undertaken to demonstrate that a very good economy may be obtained and at the same time a satisfactory uniformity of brightness. In this study a large luminous surface has been used, which involved an unusually large amount of testing in order to represent suitably the true performance of such large luminaires.

DESIGN

The basic ideas behind the design are extremely simple. The light must generally come into the room from the laylight through a diffusing translucent surface of glass, which hides the lamp and the interior of the luminaire. To get the maximum efficiency in the luminaire the inter-reflections between this translucent face and the reflecting background must be minimized; this means that the desired distribution of flux over the translucent surface, or desired distribution of brightness, must be had by directing the light as well as possible after the first reflection from the background, which requires specular reflection with careful designing of the reflector shape and careful placing of the light source with respect to the reflector. Thus the proper diffusion of light emerging from translucent glass should be attained by refraction and bending of the rays as they pass through it, rather than by multiple reflections between this glass and the reflecting background. Accordingly, the actual light flux lost through absorption in the glass will be minimized. As a means of reducing excessive brightness, immediately beneath the lamp source and due to the direct flux from the lamp, a secondary baffle or translucent plate is recommended.

That the reflecting background have the highest practicable reflection factor instigated the choice of specular Alzak aluminum. Plane surfaces were used because of their greater convenience.

The first step in the design was to select suitable exterior dimensions. A light surface six feet square was decided upon as being prac-

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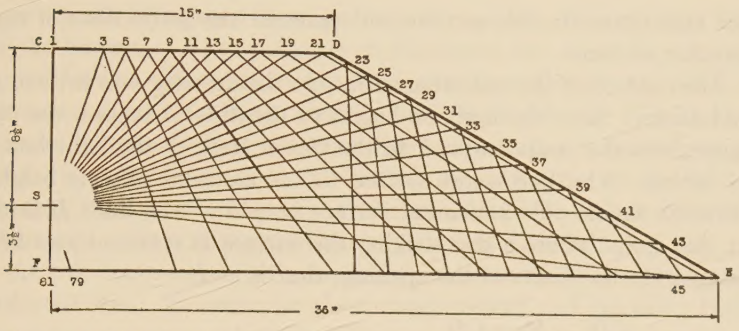

FIG. 1—A trial design of the reflector contour. For clarity in reproduction many of the rays in the original design drawing have been omitted.

tically useful and yet convenient and inexpensive enough for experimentation. Furthermore, to make the results comparable to those announced by G. V. Downer[1] for one of his laylights 12 feet by 6 feet, a maximum height or depth of luminaire of one foot was adopted; also, a single lamp was chosen as the prime source of light.

It is entirely reasonable that the lamp should be placed in the center in order to use the symmetry of the square light box. The center of the lamp was at first placed $3\frac{1}{2}$ inches above the plane of the face or opening of the light box; see Fig. 1. This spacing was chosen as being the smallest that would allow a glass diffusing plate to be placed between the glass bulb of the lamp and the sheet glass face of the light box; such a glass plate appeared to be a suitable means of reducing the high brightness at the center of the luminous surface, if it were found necessary.

In Fig. 1, *S* designates the center of the light source having assumed uniform candlepower distribution; *CD* is a horizontal specularly reflecting surface; *EF* is the opening of the light box. The contour illustrated is of a section through the center of the light box, the plane of this section being parallel to two of the bounding edges of the square opening or face of the box. The drawing illustrates only a symmetrical half of this section.

It has been assumed sufficient to design with respect to this midsection. There is some basis for the validity of this assumption if cognizance be taken of that law of optics which states that, if a ray of light is reflected at any surface, the projections of this ray upon a plane through the normal to the reflecting surface at the point of the incidence of the ray, obey the laws of reflection. This means that

the rays drawn in this section can represent the projections of rays in other sections.

The contour of the reflecting surface in the drawing was arrived at as follows. Since the limit on height or depth is 12 inches, the distance from the lamp center S to the top or back of the light box is $8\frac{1}{2}$ inches. The horizontal surface CD is assumed at this height. How far should this horizontal surface extend? The limit D is set at that point where a ray striking the surface is reflected and falls just within the limits of the opening; that is at E.

$$\frac{CD}{8.5} = \frac{36 - CD}{12} \qquad \text{Therefore: } CD = 15 \text{ inches}$$

The sloping surface is made to extend from D to E. A good reason for this straight-line contour is found in the fact that Alzak aluminum cannot be readily formed without destroying the finish and it was therefore advisable to make sharp bends in this material and thus confine the injury to the surface to a negligible area.

Thus the first trial design was made. At this point a few simple calculations were devised to prove the reflector design. For this reason it has been specified for design purposes that S is a point source and has a uniform candlepower distribution. It is mathematically convenient to consider that we have designed a surface source whose section in a plane parallel to the face of the luminous surface is a circle inscribed in the square section of the actual surface. The flux is considered as being divided up into equal bundles and if the design section is considered to be rotated around the axis of the lamp S, a small angle Θ, then equal amounts of flux are contained between every two adjacent rays. Rays 1–43 inclusive, Fig. 1, are designated as reflected flux rays and emerge usefully through the opening only after reflection. Rays 45–81 proceed to the opening directly and are therefore referred to as direct flux.

Remember cylindrical geometry is under consideration and hence the flux between any two numerically successive rays must cover a larger area as it strikes the opening farther away from the axis of the luminaire. Observe that in no case is a ray reflected more than once before reaching the opening or face of the luminaire. Random reflections have been avoided by fixing the length CD exactly. However, casual observation shows that the design allows too much light to go to the aperture directly and especially in the vicinity of the light source.

The remedy for this defect was found in the use of a suitable trans-

lucent baffle interposed between the lamp and the diffusing glass face of the luminaire. For purposes of discussion the direct flux is neglected for the time being, since the reader undoubtedly has the distribution from the lamp directly, well in mind. A plot of this distribution would show the direct flux concentration to be far greater than the reflected flux concentration, and since the direct flux is changed by the baffle almost entirely into flux of the reflected classification the subject is dispelled herewith for the time being.

At this stage some further calculations were made concerning the reflected flux. To minimize these computations and not carry them to useless extremes, reference will be made only to the odd numbered reflected rays. For example, consider the rays 3 and 5; between them is a definite amount of flux; to obtain the flux density at the face of the luminaire due to this bundle of flux is the problem. Designate the distance from F to point of crossing of the ray 3 on the line EF as R_3, and the distance from F to the corresponding point for ray 5 as R_5; designate the flux density at the face due to the flux between rays 3 and 5 as FD_{3-5} and the flux between rays 3 and 5 as K.

Then,

$$FD_{3-5} = \frac{K}{R_5^2 - R_3^2} \times \frac{2}{\theta}$$

$$\text{or } FD_{3-5} \text{ is proportional to } \frac{1}{R_5^2 - R_3^2}$$

It is assumed in this calculation that a light flux bundle impinging on a narrow annular zone of the face of the luminaire produces a uniform flux density over the zone. Obviously this assumption becomes more and more justified as one subdivides the flux into a larger and larger number of bundles for computation.

Ordinates on the graph of Fig. 2 represent the sum of all the flux densities due to the various bundles of flux effective at any given point, and abscissae correspond to points in a radial line from the axis of the luminaire, in the plane of the face.

An analysis of the flux density graph of Fig. 2 shows that the reflected flux is giving considerable aid to the already preponderantly bright center. There is no desire for reflected flux at the center of the unit.

For an efficient light box it seems reasonable to try to throw the immediately reflected flux as far as possible out toward the border of the face of the luminaire, and to use as much as necessary of the direct

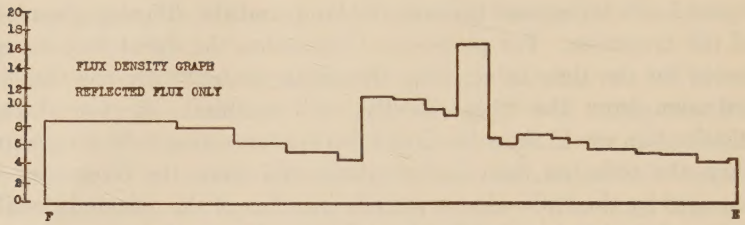

FIG. 2—This is the predicted flux density distribution for the reflected flux for the reflector contour of Fig. 1. The flux density scale used in this graph as well as in the succeeding graphs is purely an arbitrary one.

flux to produce the requisite brightness at the center of the luminaire, and to reflect by use of the baffle the remainder of the would-be direct flux so that it falls into the category of reflected flux.

The flux density graph is by no means exact; particularly, one should avoid imparting any significance to the abruptness of the flux density curve, which results only from the simplicity of our method. It was impracticable to trace some of the flux very closely, but this method of calculation is probably sufficiently accurate. In general the graph can be said to represent fairly the distribution of reflected flux. With a prospect of doing better in the way of design, Fig. 1 was never tried out experimentally.

Fig. 3 was the outgrowth of Fig. 1. The contour of the reflector was changed by cutting away the central part of the back of the reflector and substituting an inverted pyramidal sloping section *BC* so shaped and placed that any ray specularly reflected by it could not immediately thereafter strike the section *CD*. Thus the rays that strike *BC* first are permitted to strike either *EF* directly but far out

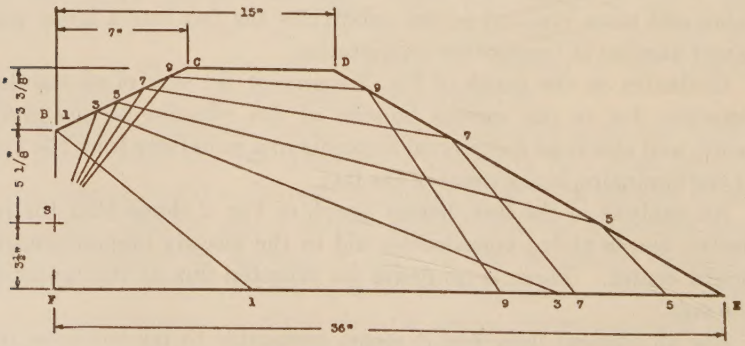

FIG. 3—Another reflector contour design. The rays in Fig. 1 which undergo a modified reflection in this new design are shown. More flux is thrown to the edges in this design.

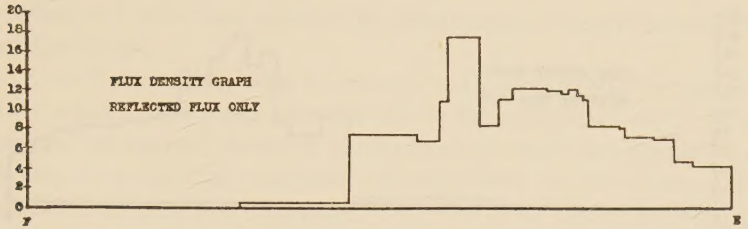

FIG. 4—The flux density distribution graph corresponding to Fig. 3. There has been a desired improvement in the flux distribution over that shown in Fig. 2 for the first trial design.

from F, or DE from which they go to EF again far out from F. Random and multiple reflections have thus been very deliberately minimized.

Fig. 3 shows that more light has been directed towards the edge than in the previous design. In the graph of the flux density for this curve, Fig. 4, it is quite apparent that an improvement has resulted in comparison with Fig. 2.

Fig. 5 is the same reflector contour as that of Fig. 3 except that the lamp position is higher or further from the face of the luminaire. Fig. 6 is the corresponding flux density graph.

The predicted distribution of density with this reflector design was promising enough to warrant the use of the design for the construction of an experimental laylight.

The reader should not attempt to relate the area of one individual flux density graph to the area of another for there exists no simple relationship.

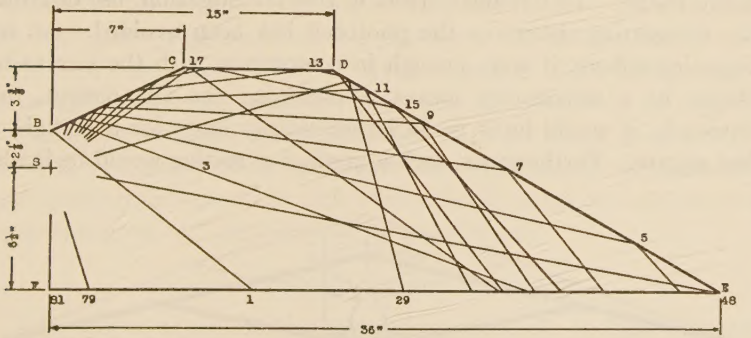

FIG. 5—The same contour of reflector as in Fig. 3. A new lamp position is shown here. The various possibilities in reflections are drawn although the plate has been simplified for clarity.

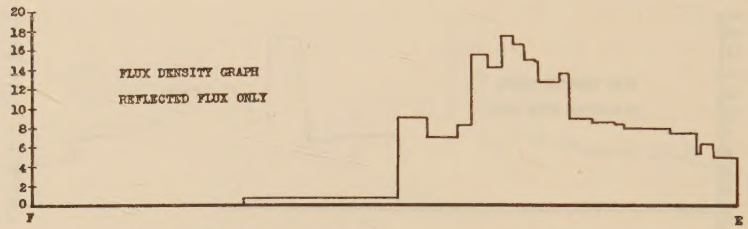

FIG. 6—The flux density distribution corresponding to Fig. 5.

The design of the baffle plate mentioned before, whose primary purpose was to prevent any direct view of the lamp filament and to reduce the brightness of the central portion of the face of the luminaire, was constructed after numerous tests had been made on the laylight without this baffle in place. The process of making the baffle was this: one side of a sheet of glass was fumed with magnesium oxide; a second sheet of glass was placed over this fumed surface; the edges of the two sheets of glass were then sealed with liquid collodion.

As stated before the reflector was formed from thin sheet aluminum with specular Alzak finish and contour as pictured in Fig. 5. The duty of avoiding images of the lamp filament and of obtaining a diffuse light and a uniform brightness at the face of the laylight has been thrust upon the enclosing glass.

TEST

In previous experimentation on luminous surfaces it has seemed to this writer that the luminous panels have not always been satisfactorily tested. To minimize errors in this investigation, use of either the integrating sphere or the photocell has been avoided. An integrating sphere, if large enough in comparison with the luminaire, should be a satisfactory means of obtaining the flux output, but obviously it would have to be impracticably large for a laylight 6 feet square. Furthermore, such a method of testing would be inade-

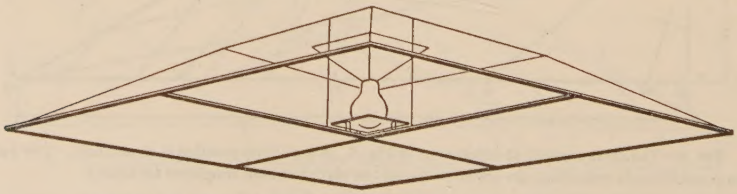

FIG. 7—This sketch shows the important design features of the laylight.

quate for it would not indicate the distribution of brightness over the surface tested.

A most convenient way to measure both the distribution and the total amount of the flux from the face of the laylight should be to use one of the several photocell illuminometers which are available, or perhaps an especially-designed illuminometer of this type. This method was tried but abandoned. A check of the results showed that serious errors resulted from specular reflections of the light rays by the glass covering of the photocell. The error was made very noticeable by the nature of the performance of the test on the laylight, which was to obtain a reading with the illuminometer at the center of each of the 144 six-inch squares into which the square face was divided. Since the luminous output was directly proportional to the sum of these readings it is quite obvious that such a method of test would invariably show a smaller value for the true flux output than is actually the case.

The means actually employed was a Macbeth illuminometer, in combination with a Taylor reflectometer used as a collecting sphere. The Taylor part-sphere was adapted for this purpose by closing the hole regularly used for the introduction of the light, and letting the light whose density is to be measured enter through the hole that would ordinarily be closed by the sample surface whose reflection factor was to be measured.

The space limits set for this paper require the omission of a great quantity of data actually obtained. Tests were made to show the difference in flux density distribution and efficiency under various conditions; the laylight was tested with and without glass, several kinds of glass being used; clear, inside-frosted, and white-bowl lamps were used; the relative effects of various portions of the reflector were determined, by using black crepe paper to kill reflections on parts of the surfaces; a series of tests were made when the Alzak surfaces were covered with glossy white cardboard, simulating glossy white enamel; and finally tests were made with various baffle plates or zone plates of various degrees and distributions of translucency.

ANALYSIS OF RESULTS AND CONCLUSION

A survey of the assembled data shows that the laylight operates more efficiently and with a better uniformity of brightness when using the specular Alzak surface than when a white enamel surface (simulated by white cardboard) is used; the use of a clear lamp in

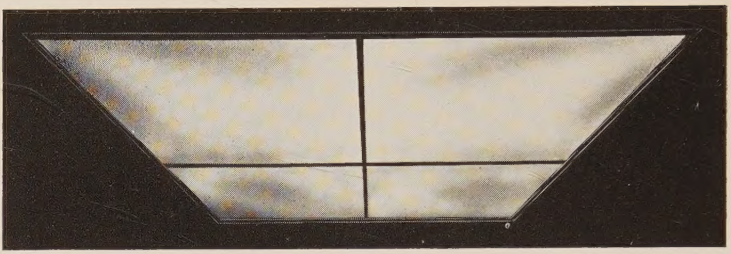

FIG. 8—The appearance of the laylight under the conditions of Run No. 27 is indeed pleasing. The luminous efficiency of the laylight as pictured is 62 per cent, while there is a brightness variation over the surface of 2.92 (ratio maximum to minimum brightness).

combination with the special baffle plate proves to be better suited to the production of a high efficiency luminaire having an acceptably uniform surface brightness, than does either the white-bowl or inside-frosted lamps; the effect of increasing the distance of the lamp to the enclosing glass is to increase the luminous efficiency of the luminaire.

FIG. 9—This shows a small part of the surface at one of the corners. The photograph has been taken under the conditions of Run No. 27. Notice how the surface is bright to the very edge of the unit. The configurations of the Pebblex glass are easily seen.

It may be said that the brightness measurements in this work have not been brightness measurements in the strict sense of directional candlepower per square inch of surface, yet a study of the photographs convinces us that our flux density values correspond very closely to brightness values; that is, any element of surface of the laylight appears equally bright in any direction. The average brightness of approximately 100 foot-lamberts is in the range of values generally acceptable for artificial skylights and windows.

The best performance of the experimental laylight showed an efficiency of 66.0 per cent and a ratio of maximum to minimum brightness of 3.4. Since a 300-watt lamp was used the actual lumens output per watt input were 12.3. This last value seems to be very significant when one considers that it has been quite customary to use luminous panels containing many lamps, each of these lamps having a bare lamp output of 12 lumens per watt or less; when we further consider that the panels containing such a multitude of small lamps had an efficiency which very often was 50.0 per cent or less, we can see that the situation has been far from satisfactory.

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